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MAN/MACHINE INTERACTION DYNAMICS AND PERFORMANCE (MMIDAP) CAPABILITY

Harold P. Frisch
Head/Robotics Applied Research
NASA/Goddard Space Flight Center (GSFC)

ABSTRACT

The creation of an ability to study interaction dynamics between a machine and its human operator can be approached from a myriad of directions. The Man/Machine Interaction Dynamics and Performance (MMIDAP) project, lead by the Goddard Space Flight Center (GSFC), seeks to create an ability to study the consequences of machine design alternatives relative to the performance of both the machine and operator. The class of machines to which this study is directed includes those that require the intelligent physical exertions of a human operator. While GSFC's Flight Telerobotic's program was expected to be a major user, basic engineering design and biomedical applications reach far beyond telerobotics. This paper outlines ongoing efforts of the GSFC and its University and small business collaborators to integrate both human performance and musculoskeletal databases with analysis capabilities necessary to enable the study of dynamic actions, reactions, and performance of coupled machine/operator systems.

INTRODUCTION

Goethe's insightful statement "The pieces I am holding in my hand, what I lack is the clarifying bond" provides an accurate definition of where GSFC's MMIDAP capability is and where it is headed. Since the project's last summary paper [1], "the pieces" have been identified, gaps recognized, and the process of creating "clarifying bonds" initiated. This paper updates the collaborative efforts of participating groups to develop a collection of marketable MMIDAP software products that will be open ended analysis capabilities. These will enable biomechanical and human performance analysis methods to be interfaced with appropriate databases. The open ended structure of the software systems will permit MMIDAP computational tools to keep pace with the state of the art by allowing the incorporation of new analysis and performance evaluation techniques.

The development of a MMIDAP capability requires both anatomical and human performance data. It requires physical testing in both the laboratory and workplace environments. Finally it requires analysis capabilities that will provide insight, understanding and the ability to extrapolate limited laboratory test data to a variety operator population groups and operational environments.

The use of MMIDAP software systems can be viewed from several different perspectives; for example:

o Mechanical and concurrent engineering will see MMIDAP providing design engineers with an ability to take human operator strengths and weaknesses into account in the early stages of machine design. The ability to obtain reliable estimates for machine operator comfort, performance, fatigue, and the potential of machine induced medical trauma during the very early pre-prototype stages of machine design will benefit both manufacturer and operator.

o Biomechanical engineering, sports medicine, orthopedics, and physical therapists, will see MMIDAP providing detail musculoskeletal system response predictions for activities associated with work and recreation.

o Rehabilitation technology service providers will see MMIDAP providing an ability to design mechanical assists and prosthesis devices to improve the quality of life for the handicapped. Furthermore, it will allow machine designers to more effectively account for the needs of handicapped operators early in the design cycle.

o Industrial ergonomists will see MMIDAP providing an ability to better understand the relationship between repetitive work and the onset of discomfort, pain, fatigue, and more serious medical problems. It will also allow job placement specialists to obtain quantifiable measures that can be used to determine if a particular employee (male, female, handicapped) has the physical resources necessary to safely operate a particular machine in the work environment for which it was designed.

JUSTIFICATION

The final report of the 1985 Integrated Ergonomic Modeling Workshop [2] contains a detailed review of pre-1988 software capability along with a list of recommendations for future research. It specifically remarks that "there is a paucity of dynamic interface models" and that "an integrated ergonomic model is needed, feasible, and useful. " The report's review of existing capability demonstrates that ergonomic modeling software has been primarily developed to support aerospace cockpit design, design for product maintainability, and whole body dynamics associated with automotive vehicle crash and pilot ejection. Some work exists under the general heading of optimization of sports motion. However, there is virtually nothing to support designers who must evaluate man/machine interaction dynamics and performance with or without survival gear, in hostile environments on earth, or in the reduced gravity environment of space.

The evolution and integration of engineering and medical sciences are bringing dynamic new problem solving capabilities within reach. A natural step commensurate with advances in analytic power involves the integration of existing knowledge and data. While gaps exist, attempts to integrate the significant pool of knowledge and data currently available would not only yield a useful end product, but would also serve to more precisely identify the location and nature of needs. While the scope of the MMIDAP project emphasizes biomechanical aspects of the human musculoskeletal system, issues are raised regarding interfaces to models of neurologic and cardiovascular systems to facilitate evolution of the basic tools envisioned.

MMIDAP DEVELOPMENT PLANS

The MMIDAP project is being planned at three levels of detail:

1. Integrated biomechanical system response and system performance. A four university team of multi-disciplinary researchers from The University of Texas at Arlington, The University of Iowa, Case Western Reserve University, and The University of Colorado at Denver have recognized the far reaching potential of this capability. A recent report [3] defines a plan for integrating existing anthropometric, musculoskeletal, and human performance databases with existing analysis capabilities. The report considers issues that impact the plan for a computer-based tool of sufficient scope and flexibility to assist both researcher and clinicians; i. e. , physical therapists, rehabilitation technology service providers, etc. Strategies with generic utility and rational for integrating anatomy (structure) as well as function and performance are presented. A standard approach to interfacing models across different levels is considered. Current data availability, gaps in data availability, data warping methods, and acquisition feasibility are reviewed in the context of supporting modeling and analysis functions in areas of practical interest and concern. It is argued therein that the need for and the relevance of this capability is based upon the following observation that: o Significant advances in analytic power can be realized through the integration of existing knowledge and discrete capabilities. o While gaps exist, a significant pool of such knowledge and data is presently available. o Technology is readily available to make implementation and dissemination feasible. o Clinical problems and research questions exist for which it is difficult to foresee solutions without the envisioned capability, thus rendering merit to the objectives. o Integration is unlikely to occur without a coordinated planning process.

2. The development of a software system to support the detailed evaluation of machine operator's task performance from the perspective of whole body response and its correlation with required levels of human performance resources needed for task completion is provided in reference [4].

3. The development of a software system to support the detailed evaluation of machine operator performance from the perspective of musculoskeletal system response and its correlation with the potential for work related pain,

discomfort, fatigue, and the more serious medical problems is provided in reference [5].

These planning efforts have highlighted the need for establishing bonds between collaborators. These bonds are effectively protocalls that allow data collected by one group to be used by another.

VISIBLE HUMAN PROJECT

The National Library of Medicine (NLM) is currently supporting a first project aimed at building a digital image library of volumetric data representing a complete normal adult human male and female [6]. This "Visible Human Project" will include digital images derived from photographic images from cryosectioning, computerized axial tomography (CAT), and magnetic resonance imaging (MRI). Members of the four-university MMIDAP project team are taking a critical view of the state of biomechanical and human performance analysis possibilities vs the state of associated data availability. It will develop a hierarchial tree of biomechanical and human performance analysis capability vs data availability, along with a plan for its realization. The emphasis is to develop the infrastructure for a systematic, engineering approach to solving human system problems and recognizing current limitations.

In reference [3], an initial plan for integrating biomechanical analysis and modeling capabilities, as well as data, into a workstation tool is defined. One problem with designing biomechanical analysis capability for the market place is that of input data development. Even the most sophisticated users find it difficult to define all musculoskeletal and human performance data needed to characterize specific human functions. In reference [6] it is recognized that the "visible human project" should eventually create an ability to both view anatomical cross sections and to query the database using functional queries. The ability to use MRI and CAT data to warp the database would provide an ability to obtain individualized detail anatomical data per subject.

ANTHROPOMETRIC AND MUSCULOSKELETAL DATABASES

A review of currently supported anthropometric data bases and computer models used in the field of ergonomics may be found in reference [2]. A source book for multiple muscle systems and movement organization, along with a survey and listing of human musculotendon actuator parameters from over 20 different published sources [7] is provided in reference [8]. Anthropometric and musculoskeletal data used to support musculo load sharing research carried on at the University of Wisconsin at Madison is provided in reference [9].

One major problem with existing biomechanical data is that they come from so many different sources, with almost as many different measurement reference frames. The NLM's Visible Human Project is presenting the biomechanics community with a unique opportunity to fill data gaps and to obtain a consistent reference source of fundamental biomechanical data.

BASIC ELEMENTS OF HUMAN PERFORMANCE

Biomechanical data alone are not sufficient for man/machine interaction dynamics and performance analysis, human function and human performance is also needed. A review of ongoing work in the quantitative measurement and assessment of human performance is provided in reference [10].

One approach to human performance task analysis is to decompose a task into fundamental components that have an associated set of quantifiable measures of performance. Kondraske refers to these fundamental components as "Basic Elements of Performance" (BEP's). BEP's have measurable attributes that can be databased according to individual and population cross section. BEPs form the basis of an elemental resource model for characterizing all aspects of the human system and explaining their relationship to tasks. As a result of multi-system measurement research, Kondraske discovered the need to first delineate general system performance theoretical constructs. A particularly attractive feature of the elemental resource model is that it is derived from a straightforward set of "first principles" that are generalizable to all systems; e.g., musculoskeletal, central processing, and life sustaining. Each BEP can be viewed as a specific functional unit and one of its dimensions of performance. For example, the functional unit (e.g. knee extensor) and one of its dimensions of performance (e.g. speed) defines a particular BEP.

Dimensions of performance identify unique qualities of performance such as speed, range of motion, accuracy, etc. Together they define a multi-dimensional performance space.

If one views BEP's as resources, then one can introduce the concept of resource availability. For example, once task decomposition into BEP's is complete, human resource requirements can be estimated. Established norms for population cross sections of interest can be used to determine if tasks are within the available resource capabilities of a particular person or of select population groups. Conversely, BEP requirements above the norm can be used to pinpoint exactly where the man machine interface needs improvement. A critical ramification of the resource construct is that it forces consideration of only those dimensions that represent desirable qualities and by definition provides a consistent method for quantifying performance. Thus,confusion resulting from dual concepts that has pervaded the field (strength vs. weakness, endurance vs. fatigue, etc.) is eliminated and a clear modeling framework emerges.

HUMAN PERFORMANCE DATABASE

Reference [11] provides a good overview of task decomposition via BEP's and methods used to database the BEP records of over 3000 patients at the University of Texas at Arlington's Human Performance Institute (HPI). This work originally was focused on the field of Physical Therapy and Rehabilitation Engineering. It is now recognized that HPI's databased information and measurement systems are identical to what is needed to support the MMIDAP project.

Task decomposition into BEP's is an attractive approach to providing a systematic basis for predicting human performance and for extrapolating experimental test data to the machine's operational environment. Unfortunately, the problem of task decomposition is non-trivial. One approach is to make use of the digital image library of the NLM's Visible Human Project. Conceptually it appears possible to create an expert system support shell that would allow users to define a high level task. Output would be a visual display of all anatomical components involved in the task and associated basic elements of performance. It seems reasonable to expect that this capability could be developed as a hierarchial structure. BEP's combine to form simple tasks, simple tasks combine to form more complex tasks, etc. Issues associated with body posture and kinematic redundancies within the human body are not being under estimated. The whole body digital mapping project intends to pursue this concept and to explore feasibility by focusing on the human knee complex in 1991.

MUSCULOSKELETAL SYSTEM MODELING

Central to the effort are the methodologies to be used for biomechanical analysis. The human musculoskeletal system is generally modeled as a mechanical system of links, joints, and actuators. Depending upon analysis fidelity, links are modeled as individual bones that are modeled as either rigid bodies, flexible bodies, or body clusters. Joints can be modeled as simple mechanical hinges or as complex anatomical joints that account for rolling and sliding contact between the irregular contact surfaces. Actuators can be modeled as resultant torque producing motors at each joint or complex force producing elements that attempt to model the musculotendon lines of action between points of origin and insertion. In theory, it is also possible to include such effects as muscle contraction dynamics and muscle recruitment to attempt to predict resultant biosystem dynamics.

General purpose software modeling capabilities exist to support this type of mechanical system modeling. The state of the art of general purpose multibody dynamics modeling is quite mature. However, biomechanics application will demand the development of enhanced capability. Reference [12] provides a reasonably complete overview of international capabilities in multibody dynamics.

Given the availability of these analysis tools, their application requires system characterization data. Kondraske of the University of Texas at Arlington has this nations most extensive database of human performance data. Seirig at the Universities of Wisconsin and Florida has most probably this nations most extensive database of skeletal and musculotendon data compatible with mechanical system analysis. Whitlock and Spitzer of the University of Colorado are under contract to the National Library of Medicine (NLM) to create whole body digital maps of both a human male and female. The MMIDAP project intends to integrate these databases. It is recognized that anthropometric and other biomedical and human performance databases exist, which will be integrated as need.

INVERSE DYNAMICS

Multibody simulation models have been successfully used to model certain classes of musculoskeletal systems. However, modeling weaknesses exist and these must be recognized before one attempts to use multibody tools for general biomechanical application. Dynamic analysis of mechanical systems is dominated by the need to solve the forward dynamics problem; i.e., given a prescribed set of internal and external loads, predict system response. Attempts to perform forward dynamic analysis with musculoskeletal systems is usually stopped by the analyst's inability to mathematically characterize the human's cognitive processes which generate the neural activation signals that stimulate the body's musculo actuator system.

The MMIDAP project recognizes this fundamental limitation. Instead, it concentrates on the inverse dynamics problem. Graphical animation and laboratory testing techniques exist for obtaining an estimate of human dynamic response for a broad range of activities. If sufficient information can be obtained (displacement, rate, acceleration, and external loads), then inverse dynamics methods can be used to predict what the resultant musculo actuator loads had to be to produce the defined input data. These results can then be compared with known human performance information to determine if predicted musculo response required by a machine operator is within the limits of capability for the machine designer's target operator population group. The exact same methods and computer programs that are used to create real-time man in the loop simulators for mechanical systems can thus be used by biomechanical groups to simulate human body response.

REAL-TIME OPERATOR IN LOOP SIMULATORS

MMIDAP intends to utilize operator in the loop simulators of complex mechanical systems to investigate environmental situations and work scenarios that have the potential for placing the machine operator in simulated harms way. These also provide a cost effective means of testing a variety of design options.

Major advances in formulating the mathematical equations needed to simulate complex mechanical equipment, along with the availability of low cost parallel processor computers have provided a unique opportunity to create low cost real-time simulators for complex mechanical equipment with the human operator in the control loop. Simulators accept real-time operator commands, predict system dynamic response, graphically create a simulated visual environment, and drive other laboratory devices to create a simulated vibrational and audio environment. Stress and load information for machine components can be obtained directly from the simulator. Qualitative control system feel and hand-eye coordination information can also be obtained from operator comments. Human performance data can be obtained by monitoring operator response in the simulated environment. The ability to simulate in real-time the gyrodynamic loads and machine force feedback control loads imposed upon the operator sets this new effort apart from that available in aircraft flight trainers.

The first step toward developing a simulator capability for complex mechanical systems was taken at the University of Iowa with its development of a simulator for the J. I. Case backhoe described in reference [13]. The ongoing second step is to create the Iowa Driving Simulator in 1991 is defined in reference [14] and the final step will be to develop the Department of Transportation's National Advanced Driving Simulator in the mid 1990's,defined in reference [15]. These capabilities can easily be modified to support the development of virtually any mechanical system to be operated by the intelligent physical exertions of a human operator.

MUSCLE MODELING AND LOAD SHARING

Detailed neuromusculoskeletal modeling of the human system or any of its subsystems is an extremely complex problem that is beyond today's state of the art capability. The First World Biomechanics Congress in August of 1990 had over 80 oral presentations on the subjects of multiple muscle systems, biomechanics, and movement organization. Formal reports on 46 of these presentations have been collected in reference [8]. From these reports and others presented at the Congress, it is clear that muscle dynamics and neuromusculoskeletal organization and movement modeling is a subject that will occupy researchers for many more years.

Complexities associated with modeling muscle contraction dynamics are matched by the problem of resolving the muscle load sharing and kinematic redundancy. The presence of redundant muscle actuators at virtually every anatomical joint implies that rules must exist for defining how muscles share the work load. An extensive summary of cost functions relevant to ongoing research in muscle load sharing at the University of Wisconsin at Madison has been provided in reference [9]. This work models the entire musculoskeletal system as a collection of hinged rigid bodies. Each muscle is modeled as a linear actuator that may wrap around bony structure and act along a resultant line of action between the points of muscle insertion and origin. To support this effort Williams, in references [16] and [17], has developed a computer program for determining muscle load sharing. The program uses Seireg's database of muscle characterization information. It computes the musculo force required by each muscle to maintain the system in quasi-static equilibrium. This work forms a major element of the work proposed in reference [5].

REPETITIVE WORK - FATIGUE, DISCOMFORT, AND INJURY

There is a good understanding of the causes of fatigue and repetitive motion injuries in industry, derived from understanding the physiology of muscle contraction and the treatment of many types of injuries. However, very little is known about how much exercise or work at any given level causes problems. Reference [5] outlines the process of validating modeling techniques associated with the investigation and prevention of industrial injury. This work will be done in collaboration with Wiker of the University of Wisconsin, director of the NASA sponsored Wisconsin Center for Space Automation and Robotics. This Center has a number of laboratories that are being made available to the MMIDAP project to conduct controlled experiments. For example, there are currently plans for Wiker and his students to investigate procedures for determining response relationships for muscle fatigue using muscle force calculations obtained from modeling software.

SUMMARY

The MMIDAP project can currently be viewed as three tightly coupled projects. Each of which can be justified independently. The union of the three however, will enable far greater capability than any of the parts. In summary:

o The four university MMIDAP team is addressing the fundamental problem of how to integrate a myriad of biomechanics and human performance related databases and analysis capabilities. Support for the disciplinary fields of sports medicine, orthopedics, prosthesis design, and neural functional stimulation are of major interest to researchers at the University of Iowa and Case Western Reserve University. Analysis needs within these fields of study will require enhancements of both existing biodynamics modeling and data collection capability. Support for the fields of rehabilitation engineering and physical therapy are of major interest at the University of Texas at Arlington. This will require the coupling of body response prediction with human performance analysis capabilities. The University of Colorado will be the provider of gross anatomy data. The matching of data analysis needs and data availability will define data gaps that can be filled as a by-product of the National Library of Medicine's Visible Human project. The details of creating an ability to associate human function with anatomy at a workstation is also being defined by the four university team.

o Photon Research Associates Inc. plans to develop the HMT-CAD (Human - Machine - Task Computer Aided Design) software system. Given a particular human body motion scenario required to achieve a particular work, recreation, or daily routine task, this software will assist in determining if a particular subject has sufficient physical resource capabilities (i.e. range of motion, strength, speed, endurance, etc.). This effort utilizes multibody dynamic analysis capabilities to predict human performance resource needs. It then couples these predictions to Kondraske's Basic Elements of Performance database at the University of Texas at Arlington to provide an estimate of task performance capability.

o R. J. Williams & Associates plans to develop the AEMUS (Analysis Engine for Musculoskeletal Systems) software system. An investigation of the potential of support from the market place has been quite revealing. While the research community is highly advanced in capability and need, the industrial market place is far less sophisticated. There is not a readily trained set of users prepared to use a capability designed by and for use in university research application. As a consequence, AEMUS must be developed in such a manner that it can grow with the sophistication of its market base. Its initial focus will be in support of industrial ergonomics and the investigation of repetitive work related problems of fatigue, discomfort, pain, and injury.

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